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The goal of this progrm is to develop a concept for an optical computer architecutre for symbolic computing by defining a computation model of a high level language, examining the possible devices for the ultimate construction of a processor, and by defining required optical operations. This quarter we investigated the implementation alternatives for an optical shuffle exchange network (SEN). Work in previous quarter had led to the conclusion that the SEN was most appropriate optical interconnection network topology for the symbolic processing architecture (SPARO). A more detailed analysis was therefore conducted to examine implementation possibilities.

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SUMMARY

The goal of this program is to develop a concept for an optical computer architecture for symbolic computing by defining a computation model of a high level language, examining the possible devices for the ultimate construction of a processor, and by defining required optical operations.

This quarter we investigated the implementation alternatives for an optical shuffle exchange network (SEN). Work in previous quarter had led to the conclusion that the SEN was most appropriate optical interconnection network topology for the symbolic processing architecture (SPARO). A more detailed analysis was therefore conducted to examine implementation possibilities.

It was determined that while the shuffle connection of the SEN was very feasible in optics using passive devices, a full-scale exchange switch which handles conflict resolution among competing messages is much more difficult. More emphasis was therefore given to the exchange switch design. The functionalities required for the exchange switch and its controls were analysed. These functionalities were then assessed for optical implementation. It is clear that even the basic exchange switch, that is, an exchange without the controls for conflict resolution, delivery, etc..., is quite a difficult problem in optics. We have proposed a number of optical techniques that appear to be good candidates for realizing the basic exchange switch. A reasonable approach appears to be to evaluate these techniques, and then incrementally add the necessary functionalities.

To evaluate the advantages of an optical design over non-optical ones, we have embarked on assessing electronic and hybrid SEN implementations in terms of complexity and performance. The hybrid design refers to the use of an electronic exchange switch in conjunction with an optical shuffle connection. Comparision of an optical design with the electronic and hybrid designs will indicate the relative feasibility of the optical design. It is quite possible, from a feasibility point of view, that the end optimal design is a hybrid of electronic and optical methods.

The tasks in the next quarter are continuations of the current ones for designing the complete exchange switch in optics. They are expected to lead to the construction of the significant optical devices or components that are required to implement the shuffle-exchange network for SPARO.

1. EXISTING OPTICAL SHUFFLE-EXCHANGE NETWORK DESIGNS

There has been increasing interest recently in the implementation of the optical perfect shuffle for sorting networks [3, 4, 5]. However, there have been very few efforts on the exchange switch implementation [6]. Here we examine the work that has been reported thus far, both on the perfect shuffle and exchange switch implementations.

1.1. Perfect shuffle

Lohmann [3] appears to be the first to present an optical perfect shuffle design. He proposes a setup using prisms and lenses (Figure 1.1). As shown in the figure, the input elements are divided into two halves, upper and lower. Next, these halves are stretched in one direction to match the size of the original inputs. Finally, the stretched halves are recombined by interlacing to achieve the perfect shuffle of the inputs. The outputs on recombination appear in reverse shuffle order but can easily be unreversed by standard optical means. The total optical path length is two times the sum of the focal lengths, f_1 and f_2, of the lenses required to separate and recombine the two halves of the input set. To maintain the same output channel spacing as that of the input. f_2 must be twice f_1. The total length is therefore $6f_1$.

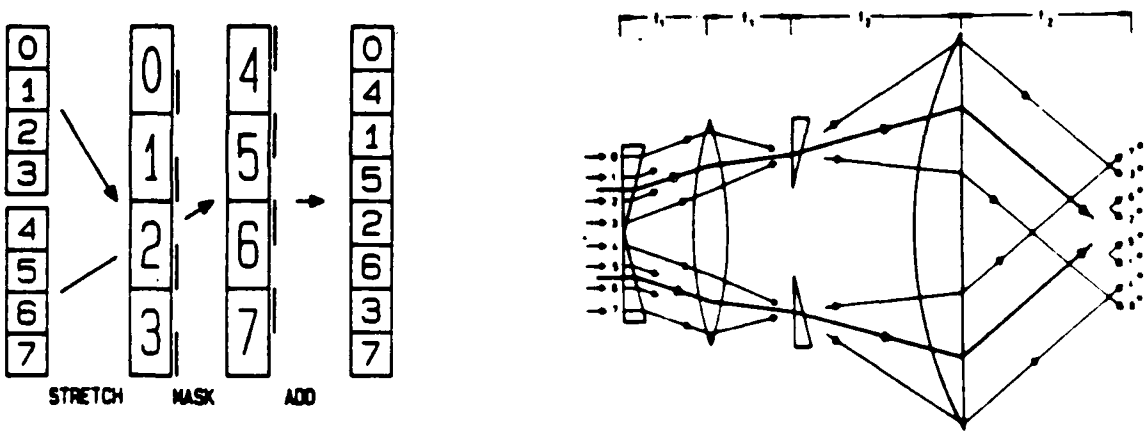

Figure 1.1. Perfect shuffle and Lohmann's scheme

Another implementation that has been proposed is one by Midwinter [5] which is suitable for one-sided operation, that is, the input and output elements are on the same side of the system. The advantage in this design is that the exchange switch logic array, which if not purely optical, can be on one side separated from the purely optical shuffle. The approach here is also, as in the previous scheme, to stretch-mask (shear)-add the inputs to obtain the perfect shuffle. However, the same optical system is folded in such a way as to incorporate a return path to the input side. The bottom half of the system only does a one-to-one imaging of the exchanged elements to the output port. Having the I/O on the same side is an advantage from the point of view of implementation. Figure 1.2 shows the folded perfect-shuffle scheme.

The third scheme by Eichmann [4] is more compact than the previous two methods. Two versions have been proposed: one in which two identical negative cylindrical lens are used side by side, and another where only one negative cyclindrical lens can be used with two prism wedges. In either case collimated input beams are

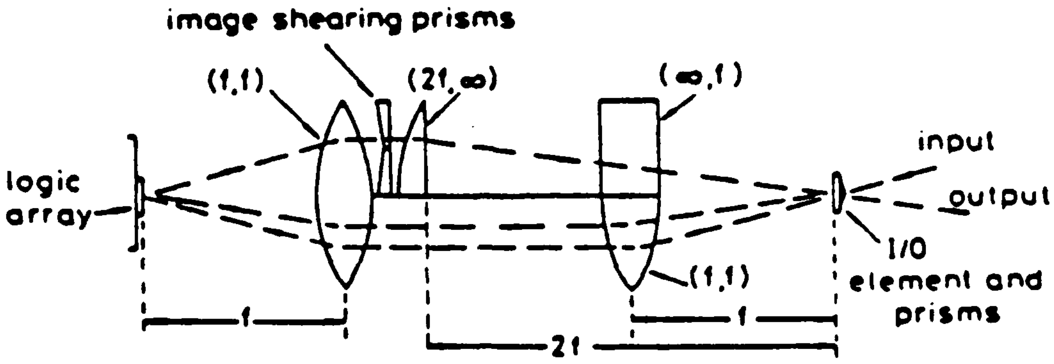

Figure 1.2 Reflected folded perfect-shuffle scheme

required. The total path length for the scheme is 2f (for the first implementation) as shown in Figure 1.3.

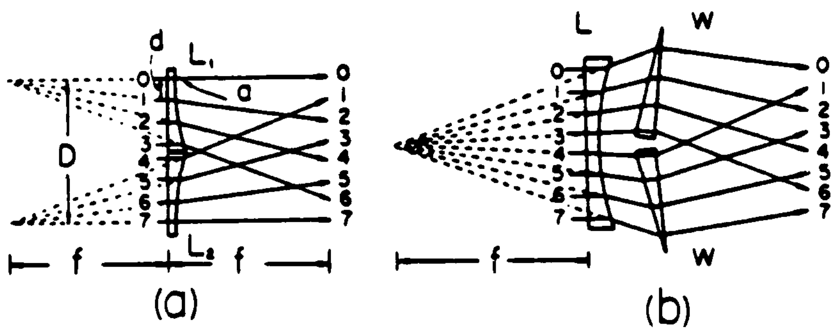

Figure 1.3 Compact perfect shuffle schemes

The unguided implementations of the optical shuffle proposed by Lohmann and Eichmann can be constructed by either holograms or by bulk optic devices as shown here. While a holographic approach is more economic, it can be operated only with monochromatic light. On the hand a costlier lens-prism approach can be used with white light illumination.

1.2. Exchange switch

The focus by most researchers has been on the realization of the perfect shuffle connection. Since the shuffle connection can be done using passive elements, the system can operate essentially at optical bandwidths. The exchange switch for the SEN cannot be realized with simple passive devices since some form of control is required to either pass uninterrupted or deflect the input beams to the output of the switch. Unfortunately, scant work is evident on designing the exchange switch. We examine some alternatives in implementing a special case of the exchange switch as described by one reported work.

Stirk, et al, [6] examine means of constructing a compare and exchange module which is assumed to always receive two inputs. The exchange is based on comparison and not on any prioritized scheme as in the case of the message passing network of

SPARO. However, some optical techniques are discussed for realizing the cross or bar (pass) configuration of the switch. Among the passive routing techniques suggested is polarization encoded switching using Wolloston prisms and controllable half-wave plates [3]. The polarizability of the half-wave plate is controlled electrooptically by some photoconductor. When the photoconductor is activated by the comparison signal, the dynamic half-wave plate rotates the polarization of the orthogonally polarized input signals through 90° (Figure 1.4). A polarizable beamsplitter or Wolloston prism can then spatially separate the two input signals. The performance of this scheme is bound by the bandwidth of the half-wave plate. These devices, due to their limited switching power dissipation, can respond at millisecond speeds. With newer ferroelectric liquid crystals, one can expect to push this response time to the microsecond range.

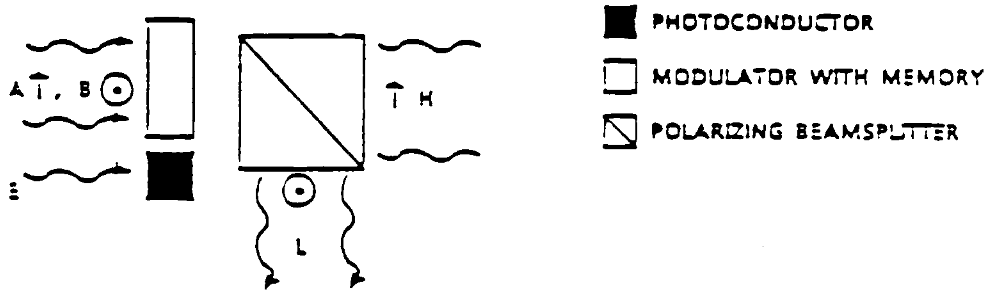

Figure 1.4 Compare and exchange implementation

An electrooptic approach has also been suggested using a system of detectors and modulators [6]. It uses nonlinear modulators which are normally transmitting unless a signal from the corresponding detectors converts them to be opaque. The scheme requires an electrical reset for the system to be operable on subsequent messages.
Use of the electrical control thus requires using electrooptic devices such as PLZTs or ferroelectric liquid crytals, the performance of which would limit the message bandwidth.

In the above proposals, the response time of the control of the switch is always the limiting factor and offsets much of the speed advantages of the purely optical shuffle. (However, there are other advantages an optical shuffle can conceivably provide over an electronic one besides speed such as increased simplicity and physical compactness.) It is important to point out, that the above designs ignore many of the key functions that are essential to the exchange switch. A simple compare and exchange module will not be useful in the case of parallel processing that uses message passing. The next section summarily outlines the important functionalities required in the exchange switch as well as in the complete network implementation.

2. REQUIRED FUNCTIONALITIES OF THE SHUFFLE-EXCHANGE NETWORK

The survey of current attempts in designing optical SENs reveals that while the basic exchange switch has been examined [3, 6], some important requirements of the exchange switch have been totally ignored. These requirements are necessary when the shuffle-exchange network is employed in a parallel processing environment such as that of SPARO. These include, for example, detecting the arrival of valid messages and the delivery of messages to their destination. We examine the impact of these required functionalities on the complexity of the switch design in the next section.

2.1. Conflict resolution by the exchange switch

The most important problem that has to be considered in a message passing environment is that of the resolution of possible conflicts among messages that arrive simultaneously at an exchange switch. Conflicts between messages occur since the correct routing of both messages may require different settings of the exchange switch.

There are a number of approaches to address this conflict depending on the desired complexity of the switch. Since one message is going to lose the conflict, these approaches differ in how to treat the losing message. One approach is to drop the losing message and let the sender processor (the source of the message) wait for a response. If a response is not received within a specified time, the sender processor will retransmit the message. The processor thus follows a specific message protocol sequence. In the case of fine-grained processing, implementing a protocol or handshake with each message is too large an overhead and therefore not acceptable. In the second approach the losing message is rerouted, that is, the message is deliberately passed through the wrong output but certain modifications are made so that it reaches its destination. In case of the single-stage SEN, the rerouting, consists of simply resetting a mask or counter that indicates the number of passes the message had made. This mask denotes the age of the message -- in a network connecting N processors, a message can be delivered in $\log_2 N$ passes when no conflicts occur. Thus to route a message, this mask is reset to 1 when the delivery is on mask value $\log_2 N$, usually represented modulo 1. No other modifications are necessary since the destination address does not change.

The resolution of the conflict or the determination of the switch setting is done in one of two ways [10]. Either the deciding message is chosen randomly or by selecting the message which has a higher mask (counter) value. It is known [2] that the prioritized selection scheme based on the mask value results in better network performance. Note that in case both messages have the same mask value, the deciding message is selected randomly.

In summary, for fine-grained computing which is fundamental to our proposed parallel architecture, resolving conflicts by rerouting is critical since loss of messages is unacceptable. Thus, the exchange switch must:

i) Resolve conflicts based on the mask (counter) values of the messages

ii) Reset the mask of the losing message, and

iii) Update the mask of message (messages) which passes (pass) successfully through the switch.

2.2. Delivery of messages

A message is delivered when it has successfully cycled $\log_2 N$ times around the network. The delivery of the messages thus requires examining the mask or counter value. If the mask value has reached $\log_2 N$, then it must be extracted from the network and delivered to the processor. This is envisioned to be simpler than comparing the destination address with the address of the processor associated with the output of each shuffle. Such a mask checking scheme would be especially attractive if the processors are operating electronically while the messages are optical signals. In this scheme, the mask of a message (or some optical equivalent) could be checked optically or electrooptically at every cycle without removing the message from the network system. When the message has indeed reached its destination, it can be sent out of the network, converted into an electronic signal and queued at the input message buffer of the processor.

2.3. Detection of a valid message

Because of the possibility of noise in an optical system, it is important that the network can distinguish a noisy null message from a valid message. Accepting noise as a real message can ruin the network performance by causing unnecessary conflicts at the exchange switches as well as send spurious data to the processors. The traditional electronic approach recommends providing a message header with each message. In the case of an optical implementation, one may either provide a header bit or stream or a separate signal which indicates if a valid message is present.

We are assuming a synchronous operation of the network so that it can work efficiently with electronic processors. A synchronous design will also be easier to design and implement. The network cycle will be synchronized with the processor array clock whose rate is determined by the speed of operation of the complete shuffle-exchange. At the beginning of each network cycle, the processors will be polled for messages generated for routing during the previous network cycle. The message present signal for every processor will therefore be examined during the beginning of every network cycle. Figure 2.1 shows the simplified schematic of the network and processor array interface. Handshake and clock signals are not shown. The message register in the network is required to hold a new message from the processor or a recirculating message from the network.

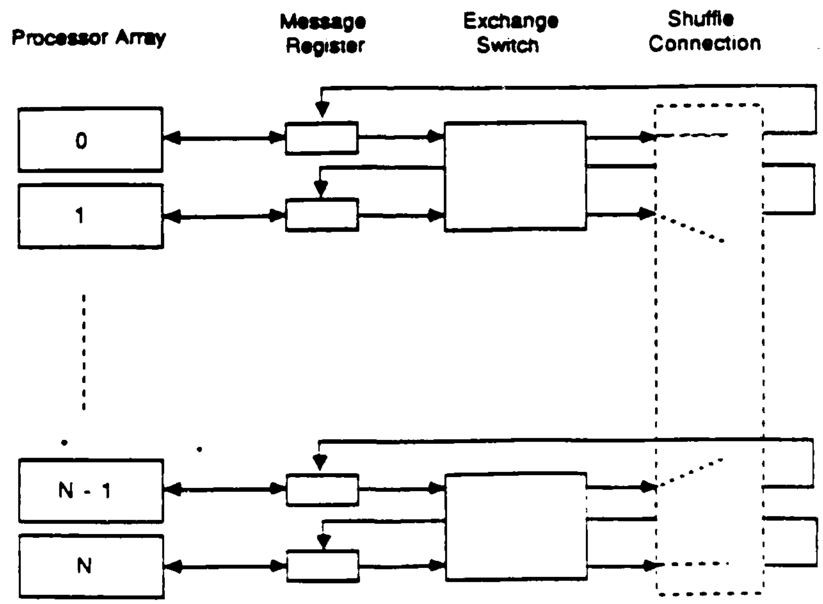

Figure 2.1 Schematic of network and processor array interface

3. OPTICAL EXCHANGE SWITCH

The most difficult part of an optical SEN is the exchange switch design. Besides implementing the conflict resolution, the exchange switch design also governs the delivery of messages (since this depends on the way masks are represented and updated). Similarly, the optical technique used for implementing the basic exchange switch, that is, the simple cross or pass switch, also determines how the controls for conflict resolution will be realized. Our initial investigation indicates that the method of representing the mask information is critical to the nature of the switch design.

In this section we discuss briefly the different candidate optical techniques that could be used for implementing the basic exchange switch. These are: acoustooptic gates, polarization encoding gates, waveguide or coupler, and photorefractive gates based on four-wave mixing. The goal is to pick the technique that results in the most speed-efficient basic exchange switch and then add the required functionalities of the network.

We also provide one exchange switch design that we have investigated using Fredkin gates [10] which have been proposed as an optical computing device [8, 9]. While no optical implementation of Fredkin gates are known, they can be viewed as a useful computing primitive from which complex computing structures can be built. We plan to evaluate the feasibility of our Fredkin gate design together with the other proposed optical techniques discussed below in the next quarter.

3.1. Polarization encoding gate

The polarization encoding gate concept requires input message signals to encode the switching information as polarization. Thus, each message can have one of two polarization levels indicating whether the switch has to be in a pass or a cross configuration. The data in each message is assumed to be intensity-encoded. The optical switch is essentially a birefringent plate with a stored grating. The grating is visible to a message beam only if the message has the 'cross' polarization, in which case the input beam is diffracted across the plate. Currently, we are examining the situations when no conflicts occur, that is both messages require a cross or pass configuration of the switch. The cross configuration can be realized by allowing a negative diffraction for the upper beam and a positive diffraction for the lower beam.

Note that this approach differs significantly from the polarization switching gate discussed by Shamir et al [8]. In that gate, signals passing through a electrooptic modulator are rotated by 90° when the gate is activated electrically. The approach presented here is purely optical. Because this method appears to hold the most promise, it is being actively pursued. However, the critical issue of conflict resolution has not been examined yet. How conflict resolution is incorporated in the switch depends on how the mask or the age of a message is encoded and updated.

3.2. Acousto-optic gate

The acoutooptic gate is not very different from the polarization switching gate of [8], except that the switching information of the exchange gate is encoded in an acoustic signal. The gate is essentially an acoustooptic deflector that can be implemented in bulk or as an integrated SAW device. If the there is no acoustic signal on the gate control line, the input messages pass undeflected, otherwise they are deflected across. The problem with this approach is that the bandwidth of messages is in acoustic range which is lower than electronic bandwidths. While this is acceptable for transfer of large messages which arrive infrequently, it is too slow for messaging in a fine-grained computing environment where the rate of computing depends on the rate at which messages can be delivered.

3.3. Photorefractive gate

A photorefractive gate based on four-wave mixing is an all-optical approach mentioned by the authors in [8]. Besides the two incident input message beams, the control consists of two pump beams. The inputs are transmitted if the control is absent, otherwise they are phase-conjugated resulting in switching between the outputs. Given the state of art in four-wave mixing, this approach appears the least feasible for implementation.

3.4. Waveguide or coupler

A modulated waveguide or fiber coupler is used for the switch. By changing the photorefractivity, one can change the coupling between the two input coupling waves. The control for the coupling is either electronic or electrooptic. Another disadvantage is that the implementation of the waveguide or coupler is usually space-intensive when integrated optics is used.

3.5. Fredkin gate implementation

Optical Fredkin gates (Figure 3.1) have been proposed recently as building blocks for optical computing. As Figure 3.1 shows, the Fredkin gate is a controlled crossover device that can be used for constructing circuit primitives (such as crossover, fanout, and delay) and computing primitives (such as AND, OR, and NOT). A Fredkin gate is also a conservative logic gate [11], that is, it is reversible (information lossless) and and bit-conservative (conserves the number of 1s and 0s that are present at the input). A control-specific Fredkin gate [9] is one in which the control and data lines are fundamentally different and cannot be interchanged.

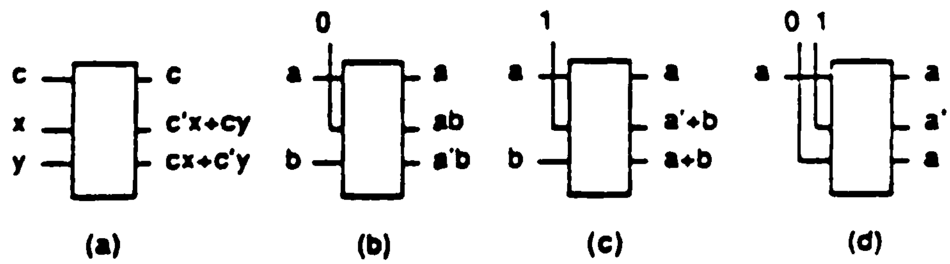

Figure 3.1 Fredkin gate and realizations of AND, OR, and NOT

We have investigated the use of Fredkin gate for realizing the exchange switch and its controls. Our approach has been to map a Boolean functional description into a circuit using Fredkin gates. We completed, as an example, a minimal Fredkin gate design [9] for the switch control. (At this stage we have ignored the mask update control.) In the next quarter we plan to examine the optical implementation of our design and evaluate its feasibility. We describe below the functional specification and the corresponding realization. The minimal circuit realization derived is control-specific with respect to the mask comparison information only.

We define five inputs to the exchange switch. These are:

P_1: Presence signal for the upper input of the switch, indicating whether a message has arrived. A 1 indicates the presence of a message while a 0 indicates no message.

P_2: Presence signal for the lower input of the switch.

M: Mask comparison signal, or the outcome of the comparison $M_1 \geq M_2$ where M_1 and M_2 are mask values of the upper and lower input messages, respectively.

A_1: The destination address bit under the mask M_1. This bit decides the switch configuration required for the message in the current network cycle.

A_2: The destination address bit under the mask M_2.

C: The output of the Fredkin gate circuit which represents the control input to the last Fredkin gate that acts as the basic exchange switch. A C value of 0 implies a straight or pass configuration while a value of 1 represents an exchange or cross configuration.

The truth table for setting the control C is indicated in Table 3.1 below.

	P_1	P_2	M	A_1	A_2	C
No Packets	0	0	-	-	-	-
One packet	1	0	-	0	-	0
	1	0	-	1	-	1
	0	1	-	-	0	1
	0	1	-	-	1	0
Two packets: No conflict	1	1	-	1	0	1
	1	1	-	0	1	0
Two packets: Conflict	1	1	1	0	0	0
	1	1	0	0	0	1
	1	1	1	1	1	1
	1	1	0	1	1	0

Table 3.1 Truth table for control of exchange gate

A logic minimization of the combinational function for C yields the following sum of products form expression. A $\neg$ before a variable name denotes the complement of that variable.

$$C = P_1 \neg P_2 A_1 + \neg P_1 P_2 \neg A_2 + P_1 A_1 \neg A_2 + P_2 \neg A_2 \neg M + P_1 A_1 M$$

Figure 3.2 shows a six gate implementation for the exchange switch in terms of the five input variables. The total propagation delay in this switch is three Fredkin gate delays .

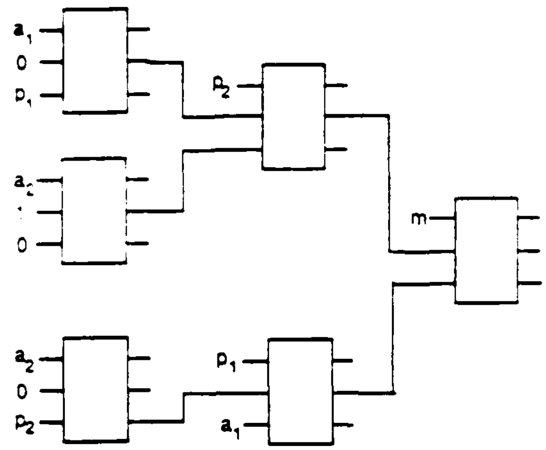

Figure 3.2 Minimal Fredkin gate implementation of exchange switch

The feasibility of the Fredkin gate implementation has yet to be determined. There have been some discussion [9] of cascading Priese gates or interaction gates to construct a single Fredkin gate but they have not been explored in detail. The speed and complexity issues of the our design will determine whether such an implementation is viable. We will study these issues in the coming quarter.

4. HYBRID ELECTRONIC-OPTICAL IMPLEMENTATIONS

To quantitatively evaluate the relative advantages of an optical SEN, we are currently examining two different SEN implementations. The first implementation is a purely electronic design of both the exchange switch and the shuffle connection. A logic design and analysis is being conducted to determine the complexity of the design in terms of silicon area and wire lengths required for connections. The same analyses will also yield the speed of operation of the SEN when the fastest semiconductor technology is used.

The second SEN implementation to be studied is a hybrid one that uses an optical shuffle in conjunction with an electronic exchange switch. The optical shuffle section is expected to be faster and more compact than a hardwired electronic implementation [7]. A similar analysis as in the case of the first will be undertaken to assess the second design. An optical SEN implementation can then be compared to both these implementations on the basis of their speed-complexity product.

5. CONCLUSIONS

We have examined the issues in constructing an optical shuffle-excahnge network. It is clear that the central problem is the design of the general exchange switch which can handle conflict resolution, message rerouting and delivery. While we have examined a number of optical techniques for realizing the basic exchange switch, a polarization encoding approach looks to be the most promising in terms of speed. The difficult issue in generalizing the basic switch into one that handles the conflict, delivery, etc. appears to be the representation of the mask or the age of the message circulating in the network.

Besides the basic switch design in optics, we have also investiagted a design based on Fredkin gates. However, we have not evaluated its feasibility. In the coming quarter we expect to continue our work on refining the optical design and also complete a comparative study of a hybrid design to determine the optimal approach in implementing the interconnection network for SPARO.

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